Glass Mirror Technology for the International X-ray Observatory

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Mirror Technology Development Team

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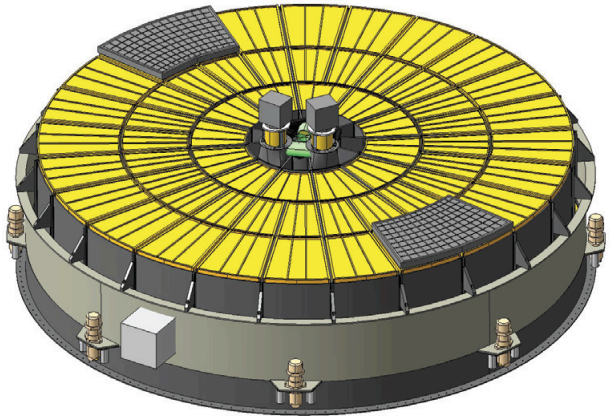
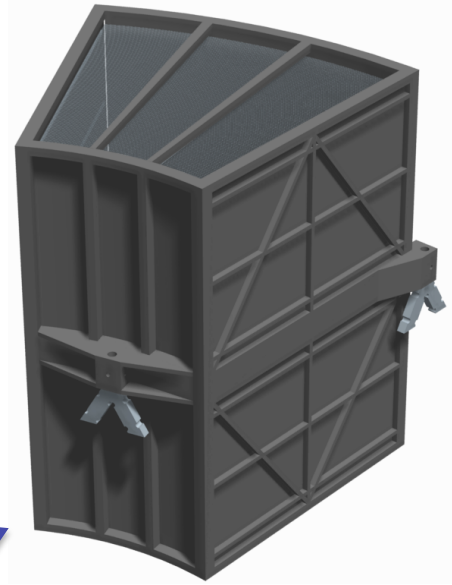
Salient Features of the Glass Mirror Technology

- Genuine Wolter-I optical design, preserving the possibility of achieving better than required 5” angular resolution
- Large mirror segment sizes, leading to more efficient packing, easily meeting and even exceeding effective area requirements

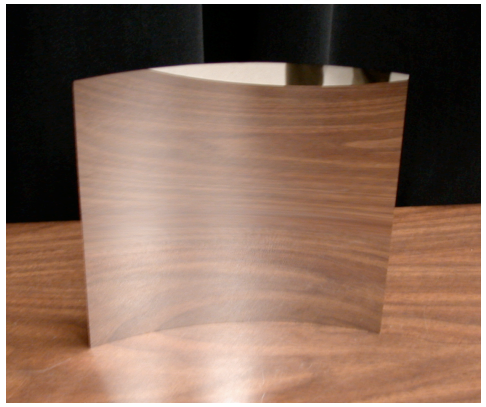
Hierarchical Structure

1 Flight Mirror Assembly





60 Mirror Modules



~15,000 Mirror Segments

Technology Components

1. **Mirror segment fabrication**
   1. Forming mandrel fabrication and qualification
   2. Slumping
   3. Coating
   4. Mirror segment metrology and qualification
2. **Module construction:** Mirror segment mount, alignment, and integration into modules
   1. Mount and temporarily bond of a mirror segment to a stiff structure
   2. Locate the mirror segment to position and orient into alignment
   3. Permanently bond the mirror segment to module housing, removing temporary stiff structure
3. **FMA Construction:** Alignment and Integration of Modules into Flight Mirror Assembly
   1. Design and fabrication of super-structure
   2. Alignment and fastening of modules

Error Allocation

Component	Individual Contribution	Running RSS	Note
Forming Mandrel	2.1”	2.1”	Two reflections based on normal incidence metrology
Mirror Fabrication	2.5”	3.3”	Two reflections based on normal incidence metrology
Mirror Pair Bonded	2.1”	3.6”	Two reflections based on normal incidence metrology
Mirror Module on Ground	1.2”	3.8”	Two reflections based on full illumination X-ray test
FMA on Ground	1.3”	4.0”	Two reflections based on full illumination X-ray tests and modeling
FMA on Orbit	2.2”	4.6”	Gravity release contribution
Observatory	1.9”	5.0”	Detectors and other factors at the observatory level

Mirror Fabrication

- Make mirror segments resemble the mandrel as closely as possible
- Use metrology every step of the process
  - to identify, quantify, and isolate every potential source of error
  - to enable the definitive prediction of point spread function for comparison with X-ray tests

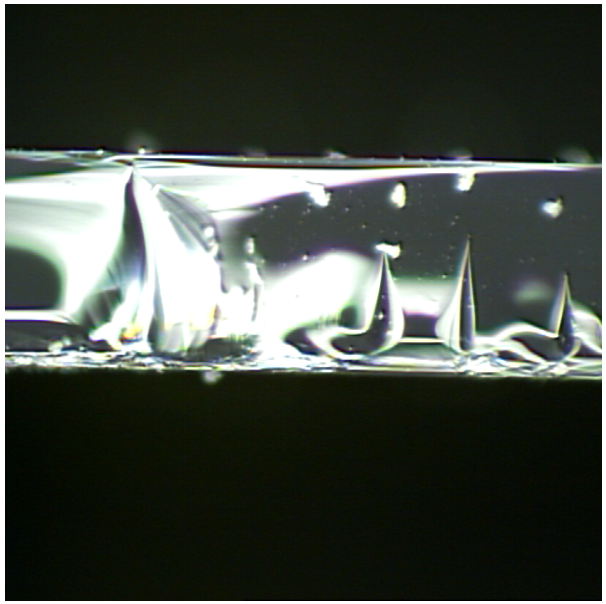
Mirror Fabrication Process

Replicating (or Slumping)

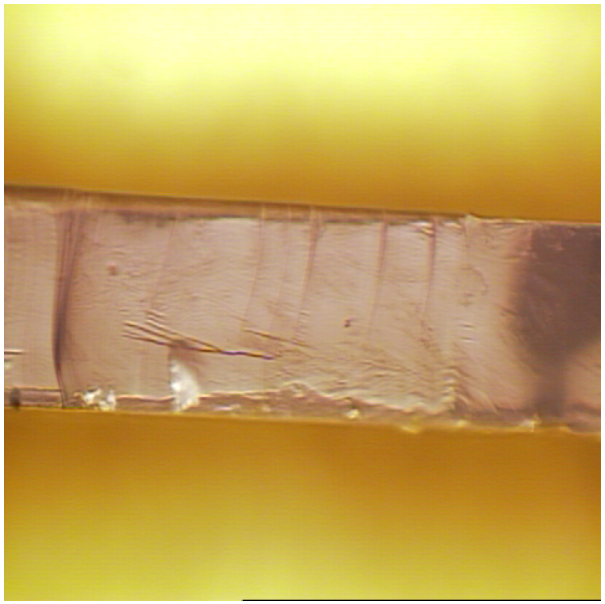
Post-slumping trimming ✔

Ir-coating ✔

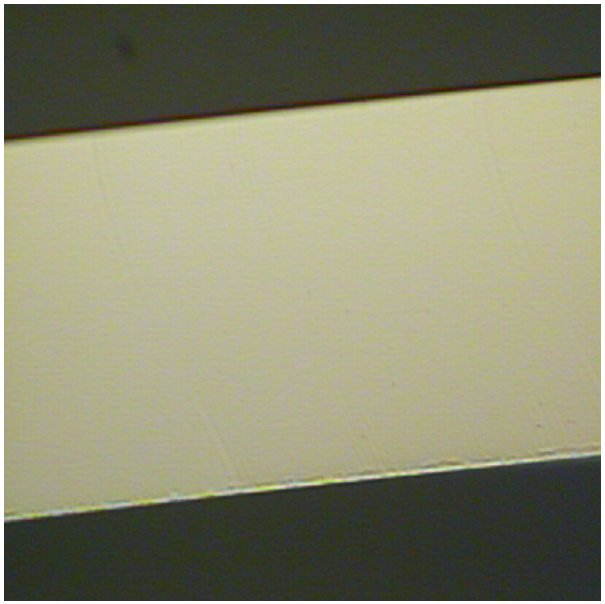
Comparison of three cutting techniques



Diamond Scriber

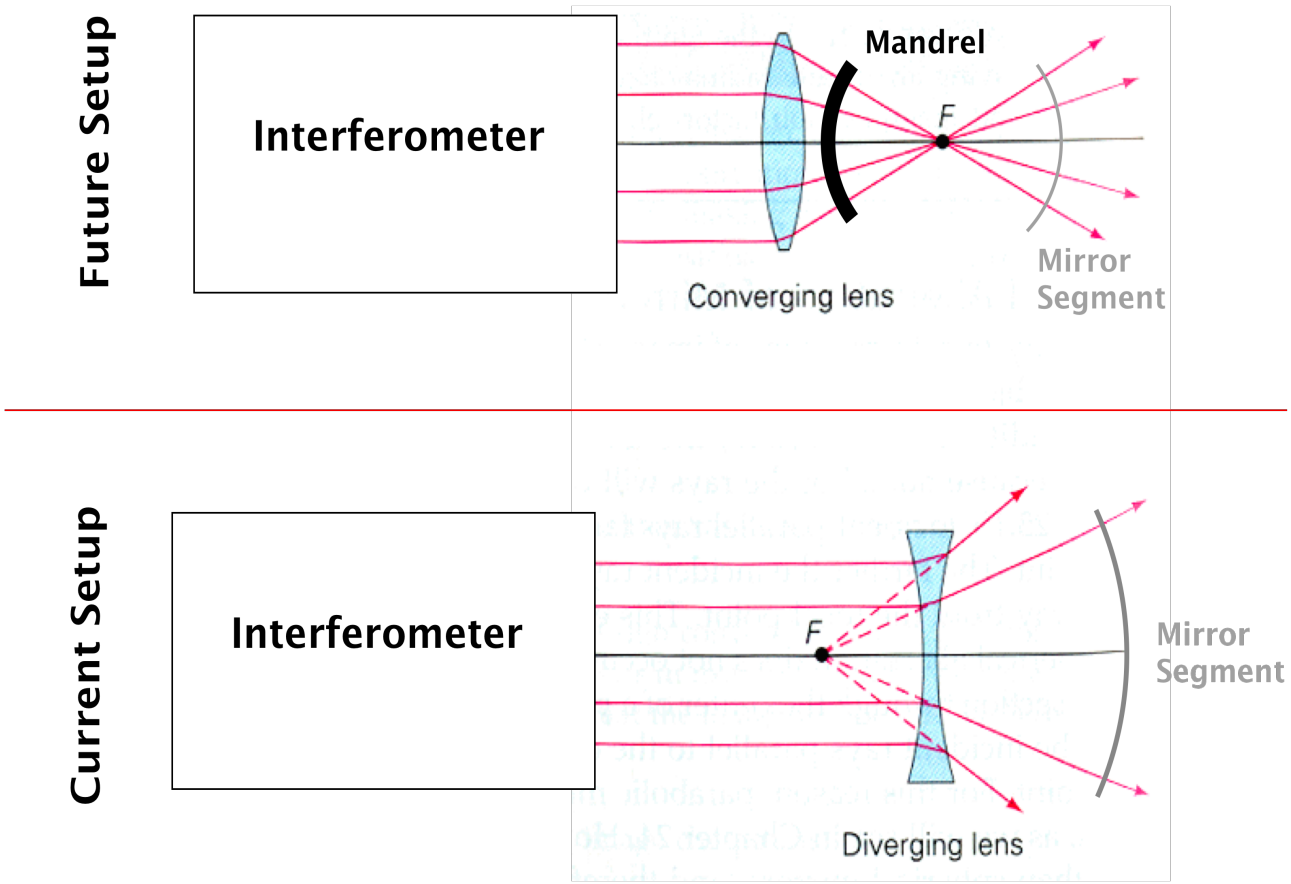


Laser Cutter



Hot Wire Cutter

Measurement System Improvement

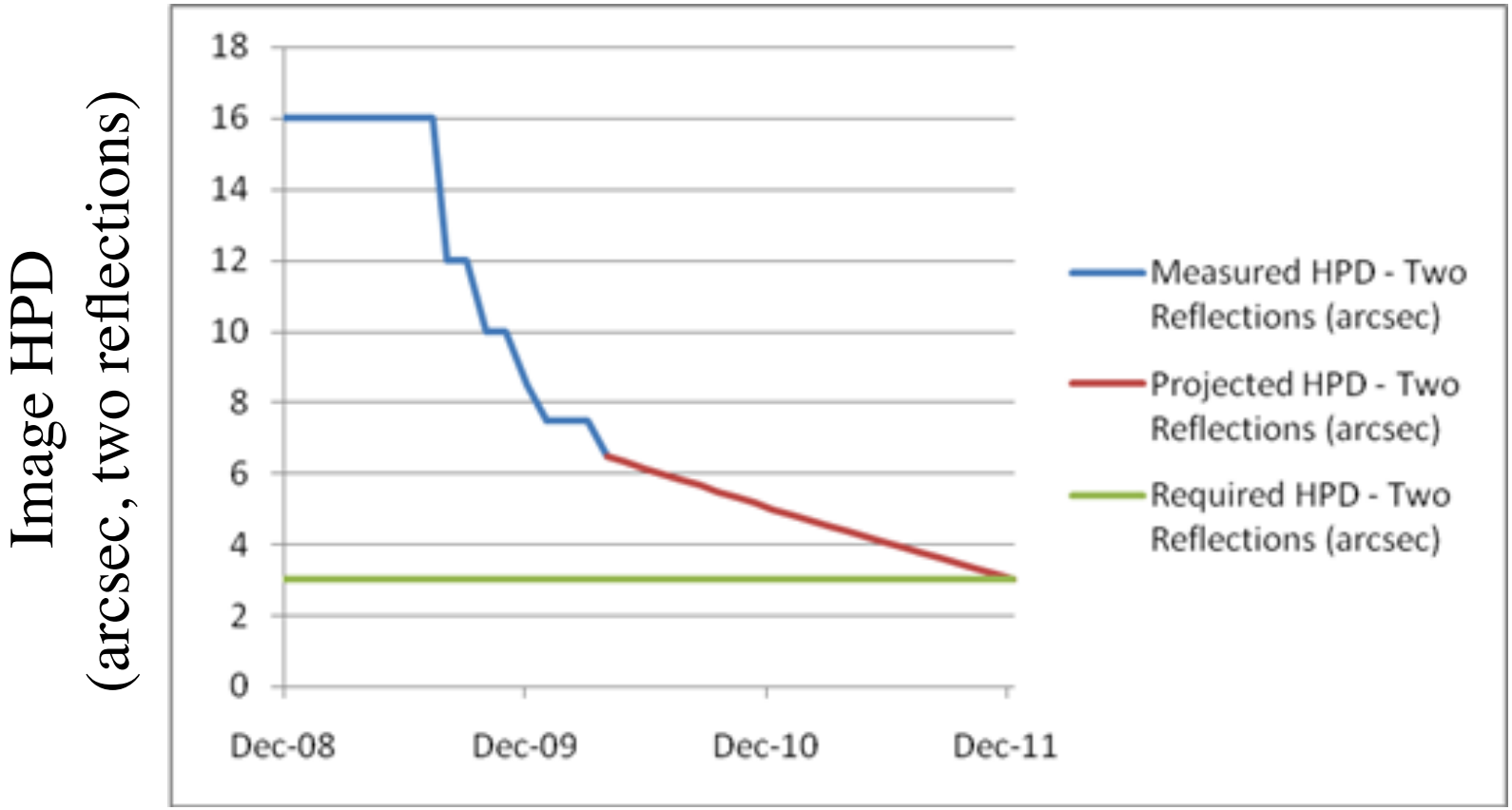


Enabling the measurement of mandrel and mirror on the same wave front

Mirror Fabrication Progress

Date	HPD (two reflections	Comment
December 2008	~16”	Normal incidence metrology, Full illumination X-ray tests; 60-deg segments
August 2009	~12”	Normal incidence metrology; 60-deg segments
October 2009	~10”	Normal incidence metrology; 30-deg segments
December 2009	~8.5”	Normal incidence metrology; 30-deg segments
January, 2010	~7.5”	Normal incidence metrology; 30-deg segments
April, 2010	~6.5”	Normal incidence metrology; 30-deg segments
December, 2010	~5”	Using mandrels meeting IXO requirements; Within a factor two of IXO mirror segment requirements
December 2011	~3”	Using mandrels meeting IXO requirements; Meeting IXO requirements

Mirror Segment Performance vs. Time



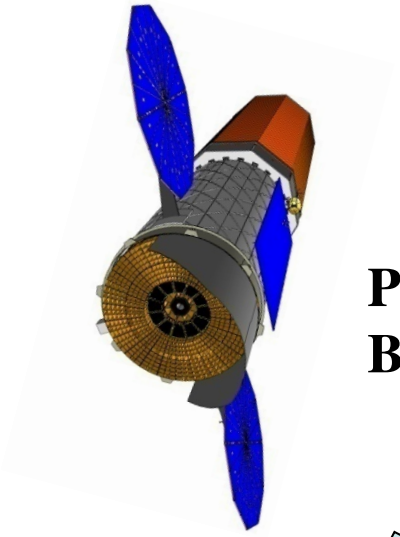
Comparison between Mandrel and Mirror Segment

Mandrels ID	Mandrel HPD (arcsec)	Mirror Segment HPD (arcsec)	Comment
485P and 485S	~7.0	7.5	Within measurement error, mirror segments are of the same quality as the mandrels
489P and 489S	~2.5	6.5	Improvement in progress, 3.0” expected for segments

Mirror Mounting

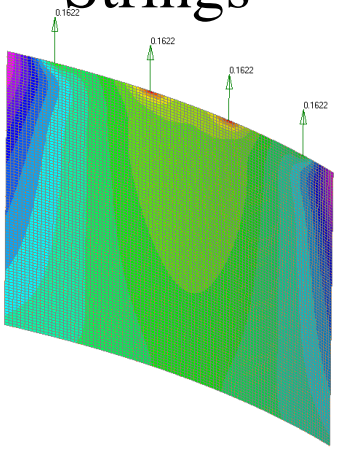
- Maintain shape of mirror as closely as possible to formed shape
  - Possibly correct 1st order errors (radius, out of round)
- Use metrology every step of the process
  - to identify, quantify, and isolate every potential source of error
  - to enable the definitive prediction of point spread function for comparison with X-ray tests

Entire Process is Analyzed and Found to Contribute 1.2” to Image Quality, Meeting Requirements

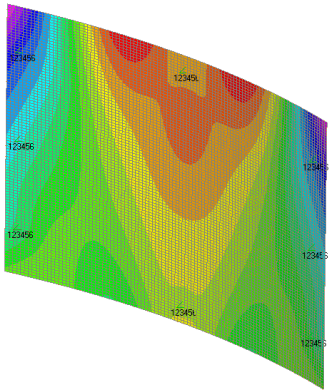


Permanent Bonded 0 g

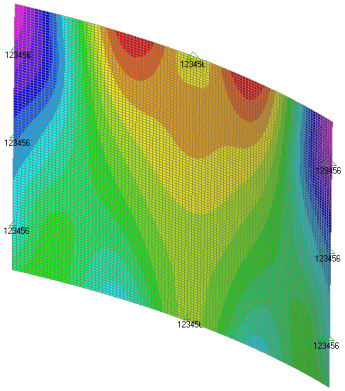
Mirror Suspended With Four Strings

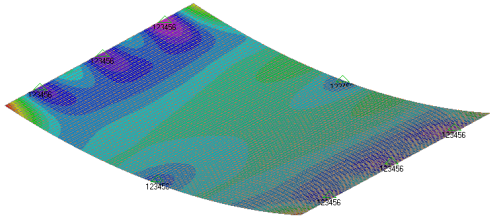


Mirror Temporarily Bonded



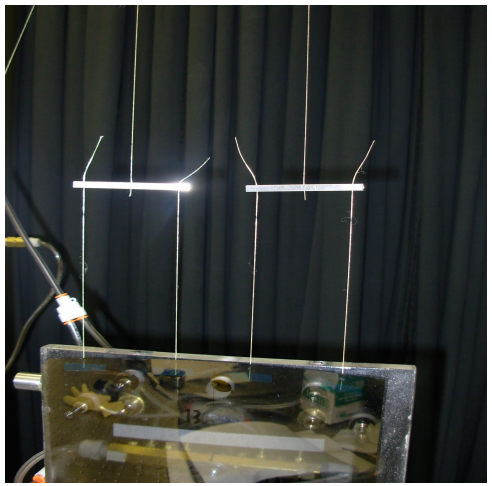
Permanent Bonded

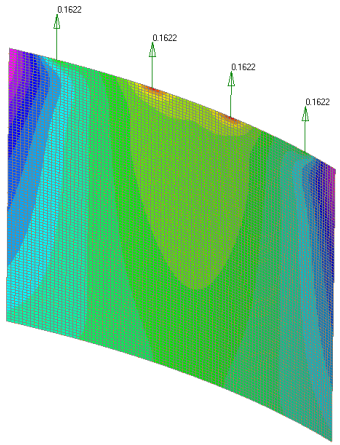




X-Ray Test

Mirror Suspended for Metrology and for Temporary Bonding

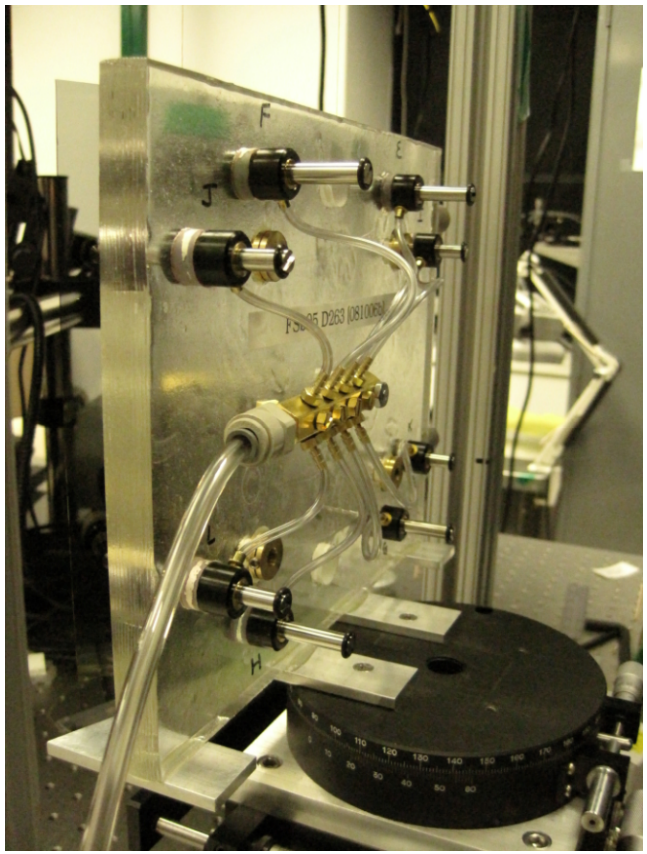


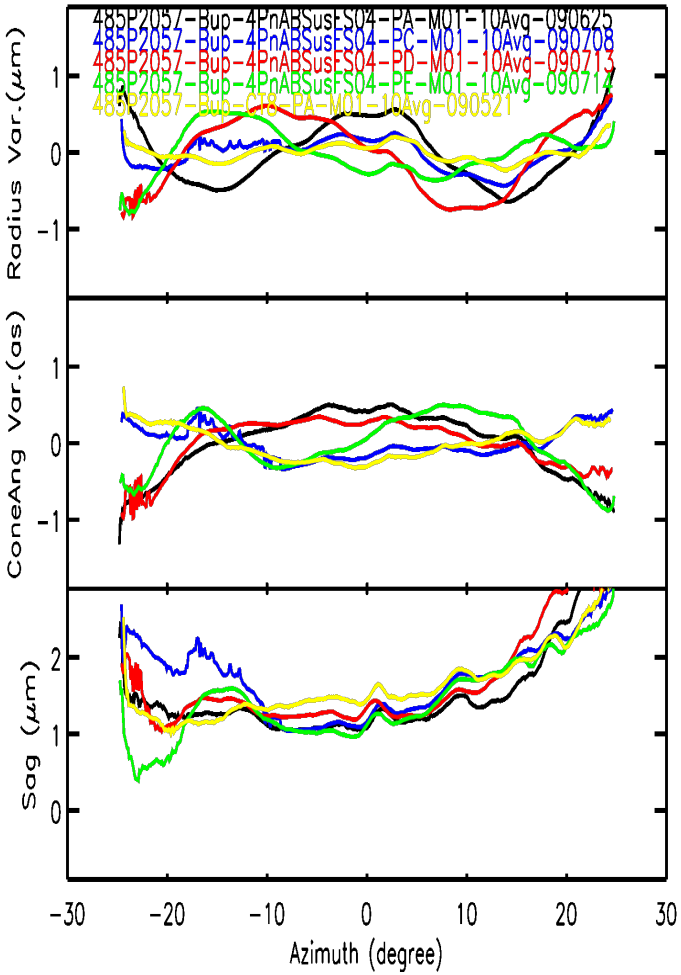


- Use 2 strings, 4 strings, or 8 strings
- All forces are deterministic and can be analyzed accurately
- In the worst case scenario, gravity distorts a perfect mirror by 0.4” HPD (one reflection)
- Being actively developed

Temporary Bonding using Air-Bearing Pins

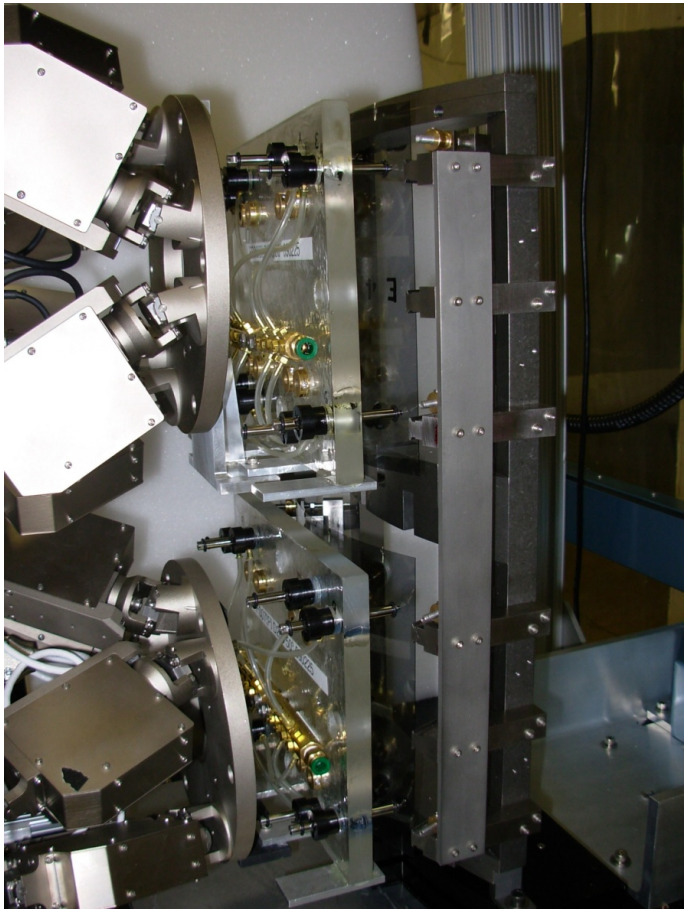
(Converting flexible mirror to Rigid Body for Alignment)

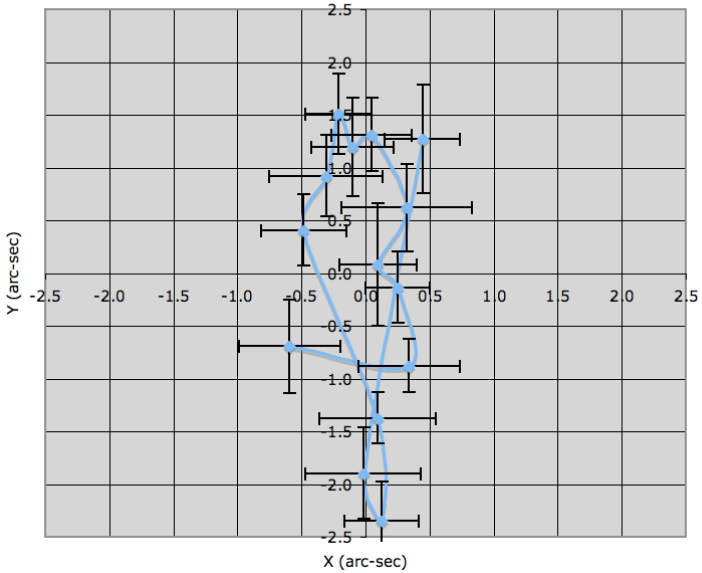




- Good repeatability
- Good speed
- Can meet TRL-4 and TRL-5 Requirements
- Need improvement to meet TRL-6 requirements

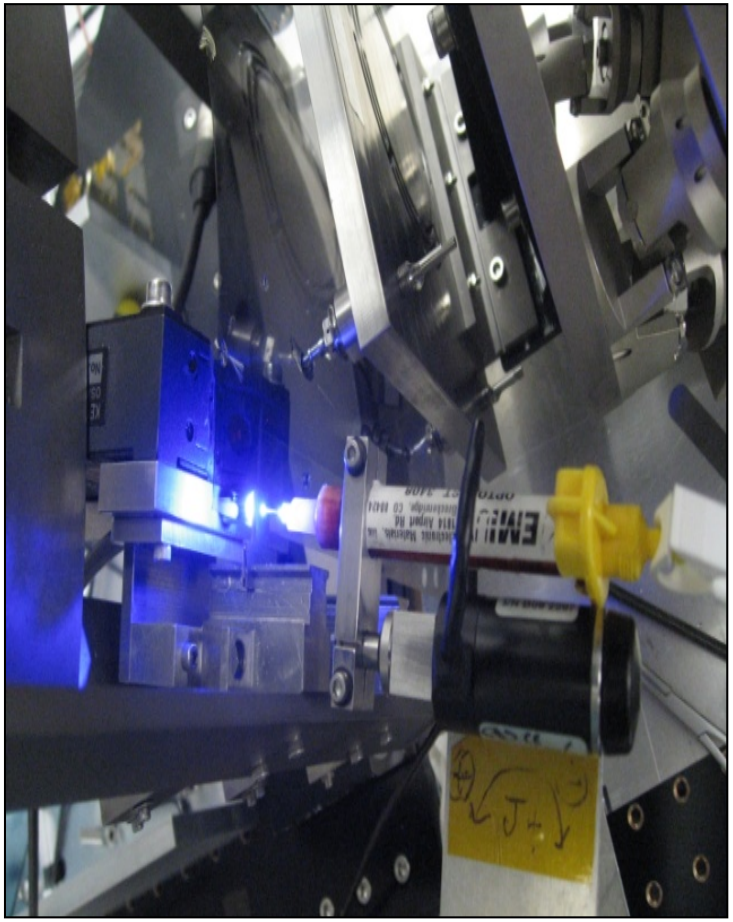
Positioning and Alignment

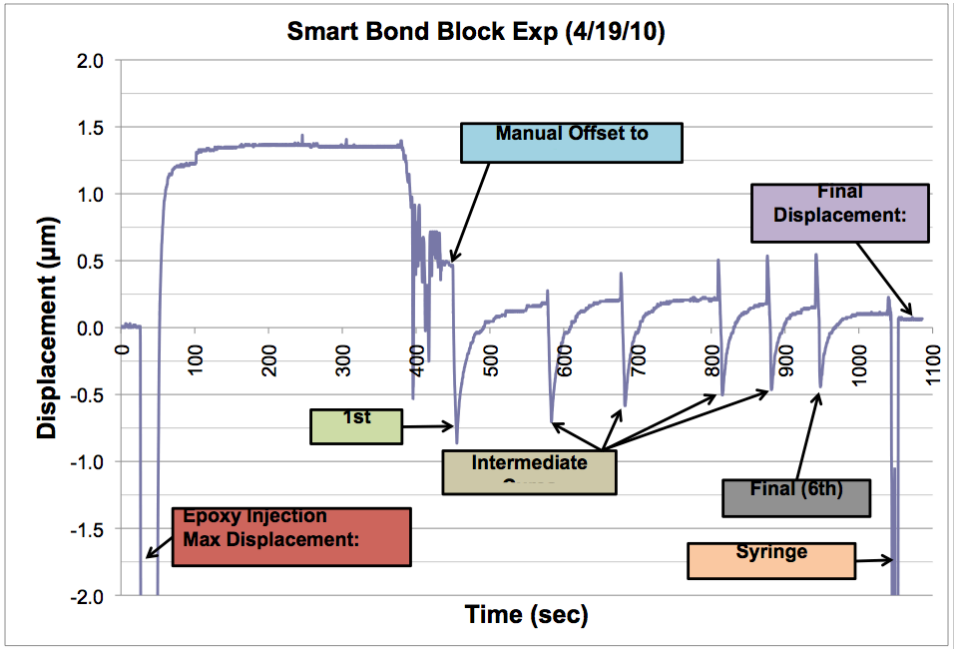




- Achieved excellent focus
- Improvement needed
  - Equipment stability
  - Lab temperature stability

Smart Permanent Bonding





- Active compensation to counter the effects of epoxy injection hydraulic and shrinkage forces
- Achieved single point bonding accuracy of 0.1μm, meeting requirements

Definitions of TRL-4,5,6 and Error Budgets

TOP-Level Description (This is what we submitted to the Decadal Survey)		TRL -4		TRL-5		TRL-6	
		Housing structure simulator; Not lightweighted; May not be suitable to withstand vibration testing; ~15 arcsecs HPD (two reflections) at one or more energies; Different tests may use different individual mirror segments; Pass tests separately; Single Pair; 60-deg mirror segments		Housing simulator; Not lightweighted; Able to withstand vibration testing; 10 arcsec HPD (two reflections), at one or more energies; Different tests may use different individual mirror segments; May pass tests separately; Complete set of tests to demonstrate agreement between model and data; Two or three pairs; 30-deg mirror segments		"Flight-like;" Fully lightweighted and modeled; Able to withstand all tests: thermal-vacuum, vibro-acoustic, and X-ray; 3.8 arcsec HPD (two reflections), at several energies spanning the IXO band of 0.1 to 7 keV; Comprehensive tests: X-ray, vibration, acoustic, thermal-vacuum, and X-ray test again to verify performance; Complete documentation; Three pairs; 30-deg mirror segments	
		Allocation for Individual Step	Running RSS	Error Allocation for Inidividual Step	Running RSS	Error Allocation for Inidividual Step	Running RSS
	Forming Mandrels (Two reflections)	7.0	7.0	2.5	2.5	2.1	2.1
	Mirror Segments (Two reflections)	10.0	12.2	6.0	6.5	2.5	3.3
Single Pair	Mounting (two reflections)	3.0	12.6	2.0	6.8	0.7	3.3
	Aligning (Two reflections)	4.0	13.2	2.0	7.1	0.7	3.4
	Permanent Bonding	4.0	13.8	2.0	7.4	0.7	3.5
Multiple Pairs	Inter-pair Alignment	0.0	13.8	2.0	7.6	0.3	3.5
	Inter-Pair Bonding	0.0	13.8	2.0	7.9	0.3	3.5
Distortions	Thermal	2.0	13.9	2.0	8.1	0.3	3.5
	Gravity	2.0	14.1	2.0	8.4	0.3	3.5
	Other (such as movement etc.)	5.1	15.0	5.4	10.0	1.5	3.8
X-ray Image HPD (arcsec; two reflections)		15.0		10.0		3.8	

Outlook

- Mirror fabrication milestones
  - Consistent at ~5” HPD (two reflections) by end of 2010
  - Consistently meeting requirements (~3” HPD two reflections)
- Improvement of metrology to identify and isolate sources of error
  - Metrology mount
  - Upgrade null lens
  - Check for systematic effects
  - Use both normal and grazing incidence measurement

Outlook (cont.)

- Mirror Alignment and Bonding
  - Meet temporary bond requirements by end of 2010
  - Meet alignment requirements by end of 2011
  - Meet permanent bond requirements by end of 2011
- TRL Milestones: Consistently mount, align, bond, and X-ray test
  - TRL-4: **single** pairs of mirror segments to achieve better than **15" HPD** by end of June 2010
  - TRL-5: **MULTIPLE** pairs of mirror segments to achieve better than **10" HPD** by mid-2011
  - TRL-6: **MULTIPLE** pairs of mirror segments to achieve better than **5" HPD** by the end of 2011

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